ANISOTROPY OF THE PIEZOJUNCTION EFFECT IN SILICON TRANSISTORS

J. F. Creemer and P. J. French
Delft University of Technology, DIMES, Electronic Instrumentation
Mekelweg 4, 2628 CD Delft, The Netherlands
Tel: +31-15-278 6285, Fax: +31-15-278 5755
E-mail: f.creemer@its.tudelft.nl

Abstract: Mechanical stress influences the saturation current of a bipolar transistor by means of the piezojunction effect. This effect can therefore serve to detect stress in micromachined sensors. It has recently been modelled for the relatively low stress levels occuring in those sensors. With the use of this model the first-order stress sensitivity of the most common transistors can be analysed. It appears that the sensitivity of vertical transistors in both {100} and {111} wafers is isotropic with respect to the stress orientation. However, the sensitivity of lateral transistors is strongly anisotropic on those wafers. This fact is visualised by a number of polar plots.

INTRODUCTION

The saturation current of a bipolar transistor is very sensitive to mechanical stress. This is due to the piezojunction effect, which is strongly related to the piezoresistive effect. Transistors have therefore often been proposed as stress sensors in micromachined devices, instead of the usual resistors [1,2]. Compared to these strain gauges, transistors have the advantages of a much better source resistance and a smaller active area. However, they have rarely been applied in practice because their strong anisotropic behaviour at low stress levels has not been well understood.

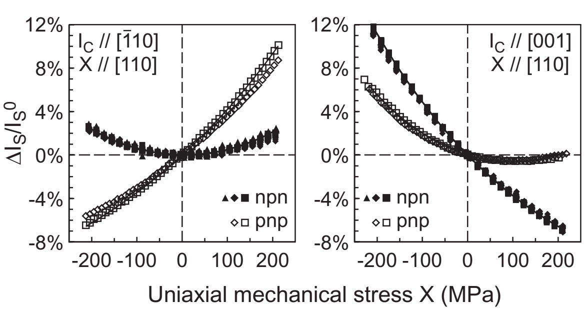

Figure 1. Measured saturation current changes of npn and pnp transistors as a function of uniaxial stress, for two different orientations of the stress X and the collector current I_c [4,5].

Table I. First-order piezojunction coefficients of silicon determined from measurements, in 10^{-11} Pa^{-1} [4].

Coefficients	Electrons	Holes
ζ_{11}	-28.4	30.8
ζ_{12}	43.4	13.8
ζ_{44}	13.1	119.8

This paper discusses the anisotropy of the piezojunction effect and illustrates it with polar plots for the most common crystal orientations. These plots can be used in sensor design to find the optimum orientation of stress and current. They are similar to the well-known plots of the piezo*resistive* effect [3]. However, they are based on the new theory of the piezojunction effect, recently presented at Transducers'01 [4,5].

THEORY

In the newly developed theory the piezojunction effect is described by a polynomial tensor series [4,5]. Any small change ΔI_S in the saturation current of a transistor I_{S0} is expressed in terms of the stress tensor X_j , the current orientation vector l_i., and the first-order piezojunction coefficients ζ_{ij}:

$$\frac{\Delta I_S}{I_{S0}} = \sum_{i,j=1}^{6} l_i \varsigma_{ij} X_j$$

In this equation, the reduced-index notation has been used which is customary in the description of the piezoresistive effect [3,6,7].

The tensor with piezojunction coefficients ζ_{ij} is a material parameter. It has the cubic symmetry of the silicon crystal and therefore contains only three independent, nonzero values. These values have been determined from experimental data like those plotted in Figure 1 [4], and are shown in Table I. The piezojunction coefficients have values which comparable to those of the piezoresistive coefficients [7].

Table II. First-order stress-sensitivity of bipolar transistors in orientations of isotropic behaviour.

Wafer plane	Current orientation	Stress Orientation	First-order stress sensitivity	*npn* 10^{-11} Pa^{-1}	*pnp* 10^{-11} Pa^{-1}
{100}	Vertical	In-plane	$-\zeta_{12}$	-43.4	-13.8
{111}	Vertical	In-plane	$-(\zeta_{11}+2\zeta_{12}-\zeta_{44})/3$	-15.1	20.5
{111}	Lateral	Longitudinal	$-(\zeta_{11}+\zeta_{12}+\zeta_{44})/2$	-7.6	-82.9
{111}	Lateral	Transverse	$-(\zeta_{11}+5\zeta_{12}-\zeta_{44})/6$	-28.2	4.0

Figure 1 also indicates that the second-order effect may not be neglected at higher stress levels or at high levels of accuracy. To include the second-order effect, the equation can be extended with second-order term. However, the nine independent coefficients associated to this term have not all been determined up to present [4,5].

PRACTICAL CONFIGURATIONS

The tensor equation can be simplified for most practical cases. Generally, transistors and sensors are fabricated on wafers of either a {100} or a {111} orientation. Transistors are either of the vertical or the lateral type, as shown in Figure 2. This means that the current crosses the base in a direction l_i which is either perpendicular to, or in the plane of the wafer. Stresses are mostly oriented in the plane of the wafer. Often they be considered as uniaxial, or as a linear combination of uniaxial stresses. The stress tensor X_j need therefore be considered only in a very limited number of orientations.

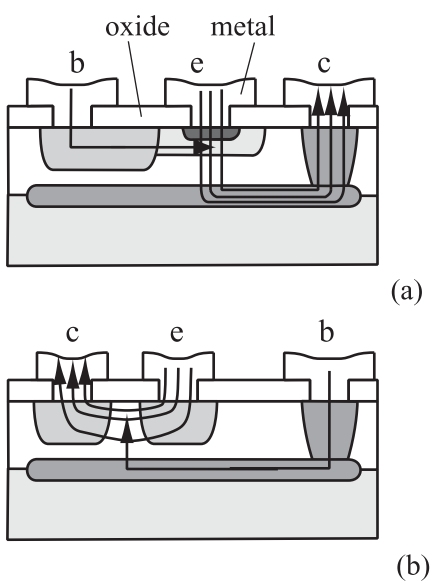

Figure 2. Cross section of a common vertical npn *transistor (a) and a lateral* pnp *transistor (b). The arrows indicate the directions of the main currents with respect to the wafer plane. The base, emitter, and collector connections are indicated with* b, e, *and* c*, respectively.*

ANISOTROPY

When the current and the stress are varied within the discussed limits, the tensor equation can be reduced to polar plots of the first-order stress sensitivity of the considered transistors. This yields some interesting results.

Firstly, it appears that the vertical transistors are insensitive to the *orientation* of in-plane stress. In a polar plot the stress sensitivities would therefore appear as concentric circles. The sensitivity to the *magnitude* of this stress is given in Table II. This sensitivity is especially large for *npn* transistors in a {100} wafer.

Secondly, it appears that lateral transistors on a {111} wafer also show isotropic behaviour when uniaxial stress is either longitudinal or transverse to the current direction. This configuration is sketched on the left hand side of Figure 3, whereas the sensitivity is specified in Table II.

Finally, a large *anisotropic* behaviour is observed for lateral transistors on a {100} wafer. This is illustrated in Figure 3 for the longitudinal and transverse sensitivity of a *pnp* transistor. The sensitivities are maximum for stress in a <110> direction. The transverse sensitivity is opposite in sign to the longitudinal sensitivity and more than two times larger. This corresponds to results reported elsewhere [8].

The anisotropy of lateral transistors is also illustrated by Figure 4 and 5. In these figures a lateral *pnp* is oriented in a standard <110> direction while only the uniaxial stress direction is rotated through the wafer plane. Also in this case the sensitivity is maximum for stress in a <110> direction perpendicular to the current, for both {100} and {111} wafers.

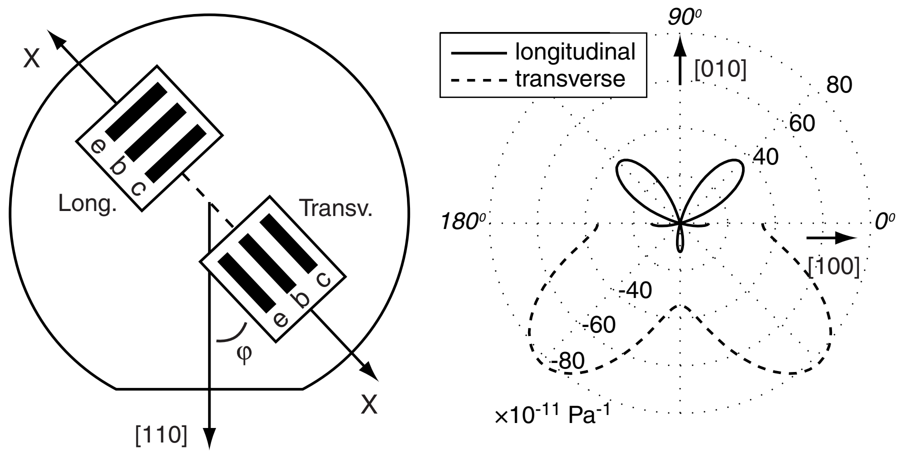

Figure 3. Left: lateral pnp *transistors on a {100} wafer subject to a uniaxial stress* X. *This stress is either oriented in the longitudinal direction with respect to the current, or in the transverse direction. Right: First-order stress sensitivity when both the stress direction and the transistors are rotated through the wafer plane.*

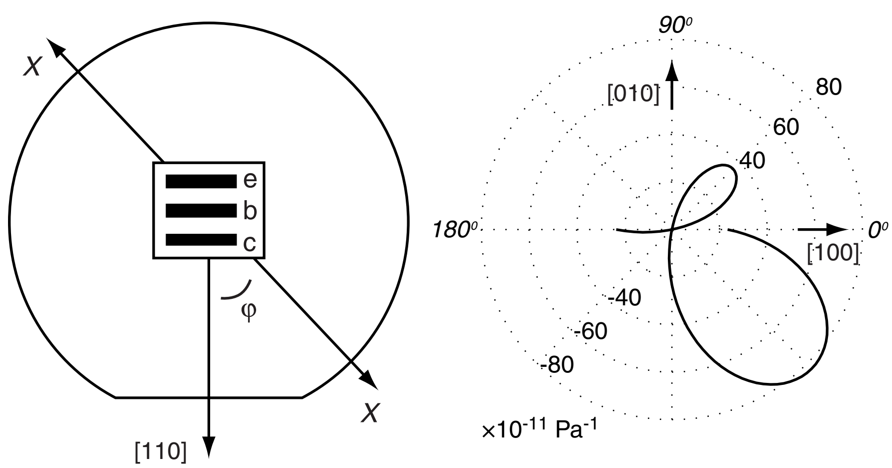

Figure 4. Left: lateral pnp *transistors on a {100} wafer in a standard [110] direction, which is subject to a uniaxial stress* X. *The stress lies in the wafer plane under an angle* φ. *Right: First-order stress sensitivity when* φ *is rotated and the transistor orientation is kept fixed.*

CONCLUSIONS

The first-order stress sensitivity of bipolar transistors has been analysed as function of the current and stress orientation with respect to the wafer plane. It appears that the sensitivity is isotropic for vertical transistors on {100} and {111} wafers. However, it is highly anisotropic for lateral transistors, especially when the transistors are oriented in a standard [110] direction and the orientation of the stress varies. For lateral *pnp* transistors the sensitivity is maximised when the stress is oriented along a <110> direction.

Thus, for the first time, bipolar transistors can be optimised for sensing mechanical stress through a detailed knowledge of the piezojunction effect in all orientations.

ACKNOWLEDGEMENTS

This research is supported by the Technology Foundation STW, applied science foundation of NWO and the technology programme of the Ministry of Economic Affairs.

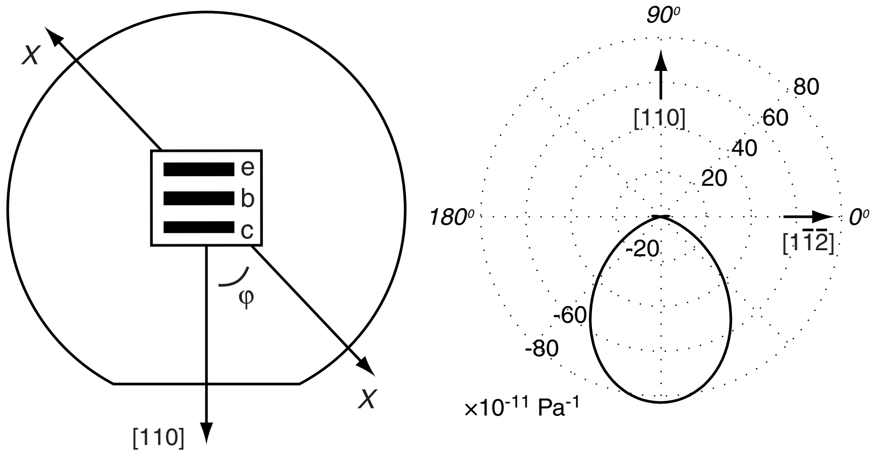

Figure 5. Left: lateral pnp *transistors on a {111} wafer in a standard [110] direction, which is subject to a uniaxial stress* X. *The stress lies in the wafer plane under an angle* φ. *Right: First-order stress sensitivity when* φ *is rotated and the transistor orientation is kept fixed.*

REFERENCES

[1] B. Puers, L. Reynaert, W. Snoeys, W. M. C. Sansen, A new uniaxial accelerometer in silicon based on the piezojunction effect, *IEEE Trans. El. Dev., ED-35* (1988) 764-770.

[2] R. Schellin and R. Mohr, A monolithically-integrated transistor microphone: modelling and theoretical behaviour, *Sens. Actuators A, 37-38* (1993) 666-673.

[3] Y. Kanda, A graphical representation of the piezoresistance coefficients in silicon, *IEEE Trans. El. Dev., ED-29* (1982) 64-70.

[4] J. F. Creemer and P. J. French, An analytical model of the piezojunction effect for arbitrary stress and current orientations, *Dig. 11th International Conference on Solid-State Sensors and Actuators (Transducers'01),* Munich, Germany, June 10-14, 2001, Vol. 1, pp. 256-259.

[5] J. F. Creemer and P. J. French, A new model of the effect of mechanical stress on the saturation current of bipolar transistors, *Sens. Actuators A, to be published in the special Transducers'01 issue.*

[6] D. A. Bittle, J. C. Suhling, R. E. Beaty, R. C. Jaeger, and R. W. Johnson, Piezoresistive stress sensors for structural analysis of electronic packages, *J. Electron. Pack., 113* (1991) 203-214.

[7] K. Matsuda, K. Suzuki, K. Yamamura, and Y. Kanda, Nonlinear piezoresistive coeficients in silicon, *J. Appl. Phys., 73* (1993) 1838-1847.

[8] F. Fruett and G. C. M. Meijer, A new sensor structure using the piezojunction effect in PNP lateral structures, *Sens. Actuators A 92,* (2001) 197-202.